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Nonlinear Harmonic Radiation from a Visible Self-Amplified Spontaneous Emission Free Electron Laser

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Scientists from the University of California, Los Angeles, Brookhaven National Laboratory, Stanford Linear Accelerator Center and Lawrence Livermore National Laboratory have demonstrated for the first time the feasibility of using nonlinear harmonic self-amplified spontaneous emission (SASE) free electron laser (FEL) radiation to produce coherent, femtosecond x-rays. Nonlinear harmonic radiation (NHR) was observed using the visible-to-infrared SASE amplifier (VISA) FEL at saturation.

The growth of synchrotron light source applications in the last few decades is due largely to the improved brightness of the x-ray beams they produce. During this same period, high power, femtosecond-laser technologies have opened new frontiers in spectroscopy and dynamics system studies. The free electron laser (FEL), which produces coherent, femtosecond, x-rays, can bridge these technologies. Due to the lack of x-ray seeds and mirrors, all proposed x-ray FELs are based on self-amplified spontaneous emission (SASE), which is a high-gain, single-pass FEL amplifier.

We report here the results from a light source called visible-to-infrared SASE amplifier (VISA) FEL, which served as research and development for the linear accelerator (linac) coherent light source (LCLS), a 1-angstrom (Å) FEL to be built at the Stanford Linear Accelerator Center (SLAC) in California. VISA exemplifies that future facilities can use SASE nonlinear harmonic radiation (NHR) to produce narrower bandwidth and harder x-rays compared to the fundamental radiation.

A major challenge for the VISA collaboration was to implement the technologies necessary to reduce the size and cost of FELs, which could be considerable for future devices. Using the high-brightness beam generated by beamline 3 of Brookhaven National Laboratory's Accelerator Test Facility, and a novel magnetic undulator built by SLAC, VISA demonstrated the shortest visible gain length to date with fundamental saturation after a distance of only 3.8 meters.

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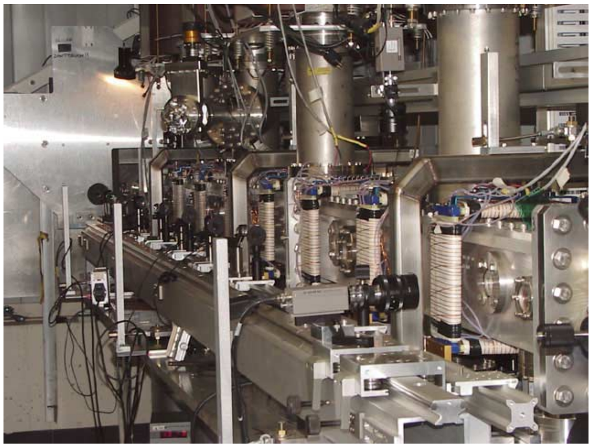
NHR accompanies the fundamental radiation only in the SASE high gain regime. Figure 1 shows the superimposed VISA spectrum at the end of the undulator for the three lowest FEL modes. The fundamental spectrum is centered at 845 nanometers (nm), and, as expected, the second and third nonlinear harmonics are centered at 422 and 280 nm, respectively.

Gain lengths for each mode are calculated from the data shown in the log-linear plot of Figure 2. A fundamental gain length of L_g =19 centimeters (cm) is measured, and NHR gain lengths of 9.8 cm and 6 cm are obtained for the second and third NHR, respectively, using only the data in the nonlinear regime. The NHR grows faster than the fundamental by $L_{g,n} = L_{g,1} / n$, verifying theoretical predictions.

By the undulator exit, the energies of the second and third NHRs are two percent and one percent of the fundamental energy, respectively, confirming theoretical predictions.

Our results show that high-gain SASE FELs generate substantial power and narrow spectra for the NHR. We measured about five megawatts of 280-nm (third harmonic) NHR, an impressive power considering our relatively small system. Extending these results, the third NHR for the LCLS will be peaked narrowly around 0.33 Å with power several orders of magnitude larger than current third-generation synchrotron light sources.



Magnetic undulator which helped to demonstrate that coherent, femtosecond x-rays can be produced by using nonlinear harmonic SASE-FEL radiation.

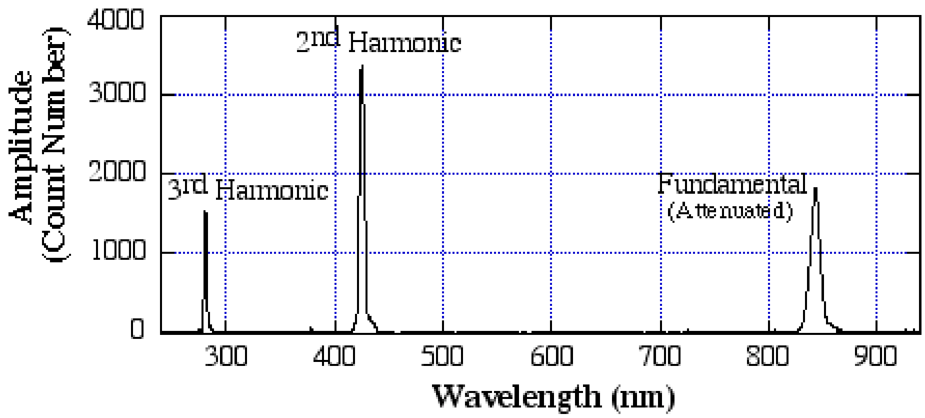


Figure 1. *SASE FEL spectra at saturation, showing fundamental, second and third harmonics. The fundamental is highly attenuated to be on the same scale as the other modes. The resolution of the spectrometer is about 1 nm.*

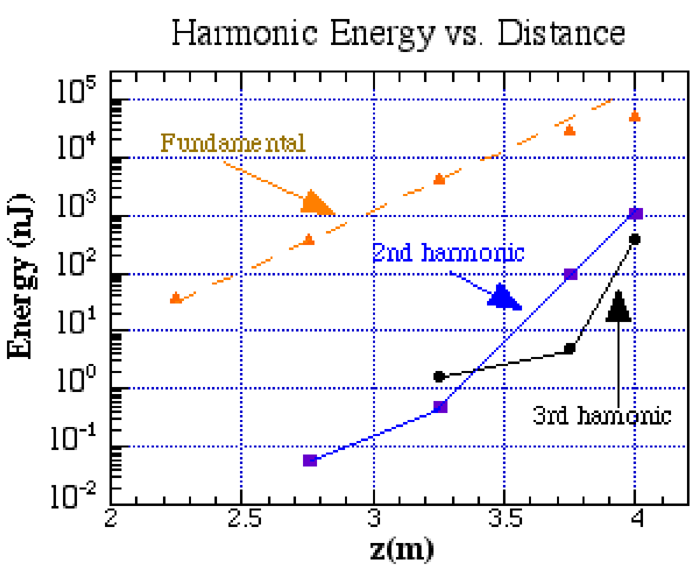


Figure 2. *Measured Energy vs. distance for the fundamental, second and third nonlinear harmonics along the second half of the 4-meter undulator. The gain lengths are 19, 9.8, and 6.0 cm respectively. The energies at the undulator exit are 52, 0.93, and 0.40 microjoules, respectively.*